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CONSTRAINTS ON RADIATIVELY INEFFICIENT ACCRETION HISTORY OF ACTIVE GALACTIC NUCLEI FROM HARD COSMOLOGICAL X-RAY BACKGROUND

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ABSTRACT

The transition of a standard thin disk to a radiatively inefficient accretion flow (RIAF) is expected to occur, when its accretion rate $\dot{m}$ is lower than the critical value $\dot{m}_{\rm crit}$ ($\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$). The RIAF is very hot, and it radiates mostly in the hard X-ray band ($\gtrsim$ 100 keV). Assuming that the accretion disk in every bright active galactic nucleus (AGN) will finally undergo a RIAF phase while $\dot{m} < \dot{m}_{\rm crit}$, we calculate the contribution of the RIAFs in AGNs to the cosmological X-ray background of $10-1000$ keV. We find that the timescale $t^{\rm RIAF}$ of the RIAF accreting at $\sim \dot{m}_{\rm crit}$ should be shorter than $\sim 10^{-2}t^{\rm b}$ if $\dot{m}_{\rm crit} = 0.01$, where $t^{\rm b}$ is the lifetime of bright AGNs, i.e., $\dot{m}$ declines from $\dot{m}_{\rm crit}$ to a rate significantly lower than $\dot{m}_{\rm crit}$ within $t^{\rm RIAF}$. The derived timescale $t^{\rm RIAF}$ is affected by the parameters adopted in the model calculations, which is also discussed in this *Letter*.

Subject headings: galaxies: active—quasars: general—accretion, accretion disks—black hole physics; X-rays: diffuse background

1. INTRODUCTION

The AGN X-ray luminosity function (XLF) is directly linked to the accretion history of AGNs in the universe. Many works on XLFs were carried out in either the soft X-ray band ($\lesssim$ 3 keV) (e.g., Maccacaro et al. 1991; Boyle et al. 1993; Page et al. 1997; Miyaji et al. 2000) or the hard X-ray band ($\gtrsim$ 2 keV) (e.g., Boyle et al. 1998; Cowie et al. 2003; Ueda et al. 2003). The luminosity functions (LFs) derived from the surveys in the soft X-ray band ($\lesssim$ 3 keV) may have missed many obscured (type II) AGNs, while the hard X-ray surveys ($\sim$ 2-10 keV) can trace the whole AGN population including obscured type II AGNs. The cosmological X-ray background (XRB) is mostly contributed by AGNs (Hasinger 1998; Schmidt et al. 1998). In the most popular synthesis models of the XRB based on the unification schemes for AGNs, the cosmological XRB from $\lesssim$ 2 keV to more than several hundred keV can be fairly well reproduced by using a template spectrum of AGNs consisting of a power-law X-ray spectrum with an exponential cutoff around several hundred keV (e.g., Matt et al. 1994; Madau 1994; Comastri et al. 1995; Gilli et al. 1999; Ueda et al. 2003). Di Matteo & Fabian (1997) alternatively proposed that the very hard X-ray background (VHXRB, the term is used here for the hard X-ray background above 10 keV to distinguish from the conventionally mentioned hard X-ray background in 2–10 keV) may be dominated by the thermal bremsstrahlung emission from the advection dominated accretion flows (ADAFs) in low-luminosity AGNs. Further detailed ADAF spectral calculations (Di Matteo et al. 1999) showed that many sources at redshift $z \sim 2-3$ with ADAFs accreting at the rates close to the critical value are required to reproduce the observed VHXRB spectral shape. Recently, Ueda et al. (2003) derived a hard X-ray luminosity function (HXLF) from a highly complete AGN sample (2-10 keV), which includes both type I and type II AGNs (except Compton thick AGNs). Based on this HXLF, their synthesis models can explain most of the observed XRB from the soft X-ray band to the hard X-ray band around several hundred keV. Their calculations slightly ($\approx$10–20%) underestimate the relative shape of the XRB spectrum around its peak intensity (see Fig. 18 in their work). Such a discrepancy can be explained provided the same number of Compton-thick AGNs with $\log N_{\rm H} = 24-25$ as those with $\log N_{\rm H} = 23-24$ is included. This implies that the contribution to the VHXRB from the radiatively inefficient accretion flows (RIAFs) in AGNs may be important, but not dominant, even if the contribution from the Compton-thick AGNs is not considered.

There are a variety of studies exploring the evolution of AGNs based on either optical quasar LFs or XLFs, or both (e.g., Haehnelt & Rees 1993; Haiman & Menou 2000; Kauffmann & Haehnelt 2000; Yu & Tremaine 2002; Wyithe & Loeb 2003; Marconi et al. 2004). A common conclusion is that the timescale of AGN activities is short compared with the Hubble timescale, though the quantitative results on the bright quasar lifetime vary from $\sim 10^7$ to $\sim 10^9$ years for different investigations. The standard optically thick accretion disks are present in bright AGNs, provided the accretion rate is high. The AGN activity may be switched off while the gases near the black hole are exhausted (see Narayan 2002, for a recent review, and references therein). While the accretion rate $\dot{m}$ ($\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$) declines below a critical value $\dot{m}_{\rm crit}$, the standard disk transits to a RIAF (e.g., Narayan & Yi 1995). The RIAF is optically thin, very hot, and its spectrum is peaked at around several hundred keV. There are numerous observational evidences indicating that the RIAFs are indeed present in many low-luminosity AGNs and in our galactic center Sgr A* (e.g., Narayan & Yi 1995; Lasota et al. 1996; Gammie et al. 1999; Yuan & Narayan 2004).

In this *Letter*, we will explore how the inefficient accretion history of AGNs is constrained by the VHXRB. The cosmological parameters $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1} have been adopted in this work.

2. MODEL

The HXLF given by Ueda et al. (2003) is so far most suitable for our present investigation, as it includes both type I and type II AGNs (except Compton thick AGNs). Assuming the accretion disk in every bright AGN to transit to a RIAF while its accretion rate is low, we derive the co-moving space number density of these faint AGNs containing RIAFs from the HXLF,

provided the accretion rate evolution is known. Based on theoretical spectral calculations for the RIAFs, strict constraints on the accretion history of AGNs can be achieved from the comparison with the cosmological VHXRB in 10 – 1000 keV.

2.1. *Space density of faint AGNs*

We assume that all AGNs described by the HXLF have standard accretion disks (we will come to justify this assumption in the Discussion section). Hereafter, we refer to these AGNs with standard disks as "bright AGNs", while those AGNs with RIAFs as "faint AGNs". The X-ray luminosity in 2 – 10 keV can be converted to the bolometric luminosity by using an empirical relation: $L_{\rm bol} = f_{\rm cor}L_{\rm X}$, where $f_{\rm cor} = 100$ is adopted (Elvis et al. 2002; Menci et al. 2004). The black hole mass density for bright AGNs in the co-moving space at redshift z can be calculated by

$$\rho_{\rm bh}^{\rm b}(z) = \frac{f_{\rm cor}}{\dot m^{\rm aver}L_{\rm Edd,\odot}}\int\limits_{41.5}^{48} L_{\rm X}\frac{{\rm d}\Phi(L_{\rm X},z)}{{\rm dLog}L_{\rm X}}{\rm dLog}L_{\rm X}\quad {\rm M_\odot Mpc^{-3}}, \quad (1)$$

where $\Phi(L_{\rm X},z)$ is the HXLF given by Ueda et al. (2003), $\dot m^{\rm aver}$ is the average dimensionless accretion rate for bright AGNs described by this HXLF, and $L_{\rm Edd,\odot} = 1.38\times10^{38}{\rm ergs\ s^{-1}}$ is the Eddington luminosity for a black hole with solar mass.

In this *Letter*, we assume that the black hole mass does not change significantly after the accretion mode transition, which is satisfied only if we consider the time after the transition is shorter than the Salpeter timescale, because the accretion rates of these faint AGNs are very low ($\dot m \lesssim 10^{-2}$). The total monochromatic X-ray luminosity of all faint AGNs in unit of co-moving volume is given by

$$L_{\rm X}^{\rm f,tot}(z) = \int n^{\rm f}(M_{\rm bh},z){\rm d}M_{\rm bh}$$
$$\times \int\limits_0^{L_{\rm X}^{\rm crit}(M_{\rm bh},E)} \frac{1}{t^{\rm f}}\left[\frac{{\rm d}L_{\rm X}(E,t)}{{\rm d}t}\right]^{-1}L_{\rm X}(E){\rm d}L_{\rm X}(E), \quad (2)$$

where $n^{\rm f}(M_{\rm bh},z)$ is the black hole mass function for faint AGNs, $L_{\rm X}^{\rm crit}(M_{\rm bh},E)$ is the X-ray luminosity of the RIAF accreting at $\dot m = \dot m_{\rm crit}$. For simplicity, we employ a conventionally adopted assumption of a fixed lifetime $t^{\rm f}$ and the same light curve for all faint AGNs. For the RIAFs in AGNs, their spectra $L_{\rm X}(E)$ depend almost linearly on the black hole mass $M_{\rm bh}$, and Eq. (2) can be re-written as

$$L_{\rm X}^{\rm f,tot}(E,z) = \frac{1}{t^{\rm f}}\int\frac{M_{\rm bh}}{10^8{\rm M_\odot}}n^{\rm f}(M_{\rm bh},z){\rm d}M_{\rm bh}\int\limits_0^{t^{\rm f}} l_{\rm X}(E,t){\rm d}t$$
$$= \frac{1}{t^{\rm f}}\frac{\rho_{\rm bh}^{\rm f}(z)}{10^8{\rm M_\odot}}\int\limits_0^{t^{\rm f}} l_{\rm X}(E,t){\rm d}t, \quad (3)$$

where $l_{\rm X}(E,t)$ is the faint AGN light curve for a $10^8{\rm M_\odot}$ black hole, and it can be calculated provided the time-dependent accretion rate $\dot m(t)$ is known. The total number density $N^{\rm f}(z)$ of faint AGNs is: $N^{\rm f}(z) = N^{\rm b}(z)t^{\rm f}/t^{\rm b}$, where $t^{\rm b}$ is the liftime of bright AGNs, and the bright AGN number density $N^{\rm b}(z)$ can be calculated from the HXLF. The black hole mass density $\rho_{\rm bh}(z) = N(z)M_{\rm bh}^{\rm aver}$, where $M_{\rm bh}^{\rm aver}$ is the average black hole mass. The average black mass for faint AGNs should be larger than that for bright AGNs, as the black holes in bright AGNs are still growing through accretion (a rough estimate can give the average hole hole mass in faint AGNs being about twice of that in bright AGNs, if $\dot m^{\rm aver} = 1$ and $t^{\rm b} \sim 10^8$ years). This leads to

$$\rho_{\rm bh}^{\rm f}(z) = \frac{t^{\rm f}}{t^{\rm b}}\rho_{\rm bh}^{\rm b}(z)f_{\rm bh}, \quad (4)$$

where $f_{\rm bh} > 1$ is the ratio of average black hole masses of faint AGNs to bright AGNs. The black hole mass density for faint AGNs can be calculated from the HXLF by using Eqs. (1) and (4), so that Eq. (3) can be re-written as

$$L_{\rm X}^{\rm f,tot}(E,z) = \frac{\rho_{\rm bh}^{\rm b}(z)}{10^8{\rm M_\odot}}\frac{f_{\rm bh}}{t^{\rm b}}\int\limits_0^{t^{\rm f}} l_{\rm X}(E,t){\rm d}t. \quad (5)$$

Based on the RIAF models, the X-ray light curve can be calculated, if we know how the accretion rate $\dot m$ evolves with time. Unfortunately, we are still ignorant of the detailed form of $\dot m(t)$. Here, we introduce a timescale $t^{\rm RIAF}$ to describe the basic feature of the evolution of RIAFs in these faint AGNs,

$$\int\limits_0^{t^{\rm f}} l_{\rm X}(E,t){\rm d}t \simeq l_{\rm X}(E,0)t^{\rm RIAF} = l_{\rm X}^{\rm crit}(E)t^{\rm RIAF}. \quad (6)$$

This timescale $t^{\rm RIAF}$ describes how fast the accretion rate of a RIAF declines from $\dot m_{\rm crit}$ to a rate significantly lower than $\dot m_{\rm crit}$ after the accretion mode transition. Now, Eq. (5) becomes

$$L_{\rm X}^{\rm f,tot}(E,z) = \frac{\rho_{\rm bh}^{\rm b}(z)}{10^8{\rm M_\odot}}\frac{t^{\rm RIAF}f_{\rm bh}}{t^{\rm b}}l_{\rm X}^{\rm crit}(E). \quad (7)$$

The contribution from the RIAFs in all faint AGNs to the cosmological XRB can be calculated by

$$f_{\rm X}(E) = \int\limits_0^{z_{\rm max}} \frac{L_{\rm X}^{\rm f,tot}[(1+z)E,z]}{4\pi d_{\rm L}^2(1+z)}\frac{{\rm d}V}{{\rm d}z}{\rm d}z$$
$$= \frac{1}{10^8{\rm M_\odot}}\frac{t^{\rm RIAF}f_{\rm bh}}{t^{\rm b}}\int\limits_0^{z_{\rm max}} \frac{\rho_{\rm bh}^{\rm b}(z)l_{\rm X}^{\rm crit}[(1+z)E]}{4\pi d_{\rm L}^2(1+z)}\frac{{\rm d}V}{{\rm d}z}{\rm d}z. \quad (8)$$

In this *Letter*, we conservatively adopt $f_{\rm bh} = 1$.

2.2. *RIAF spectra*

In order to calculate the contribution of RIAFs in faint AGNs to XRB, we need to have the X-ray spectrum $l_{\rm X}^{\rm crit}(E)$ of a RIAF around a $10^8{\rm M_\odot}$ black hole accreting at the critical rate $\dot m_{\rm crit}$. We employ the approach suggested by Manmoto (2000) to calculate the global structure of an accretion flow surrounding a Schwarzschild black hole (i.e., $a = 0$) in general relativistic frame. All the radiation processes are included in the calculations of the global accretion flow structure (see Manmoto 2000, for the details and the references therein). Unlike Manmoto (2000)'s calculations, which are limited to the cases without winds, we also calculate the cases with winds. In the spectral calculations, the gravitational redshift effect is considered, while the relativistic optics near the black hole is neglected. This will not affect our final results on the XRB, as the faint AGNs should have randomly distributed orientations and the

stacked spectra would not be affected by the relativistic optics.

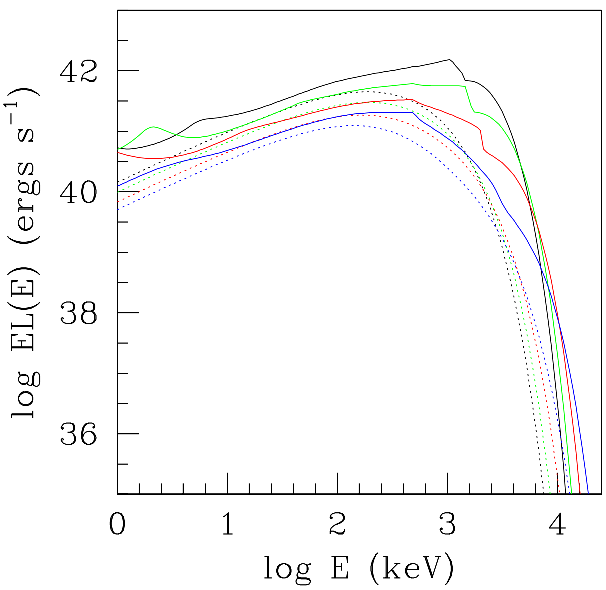

FIG. 1.— The spectra of RIAFs accreting at the critical rate $\dot{m}_{\rm out} = 0.01$, for different wind parameters: $p_{\rm w} = 0$(black), 0.2(green), 0.5(red), and 0.9(blue), respectively. The black hole mass $M_{\rm bh} = 10^8 {\rm M}_\odot$, viscosity parameter $\alpha = 0.2$, the fraction of the magnetic pressure $1-\beta = 0.5$, and the outer radius $R_{\rm out} = 100 R_{\rm Schw}$ are adopted in the calculations. The dotted lines represent the bremsstrahlung spectra of the RIAFs.

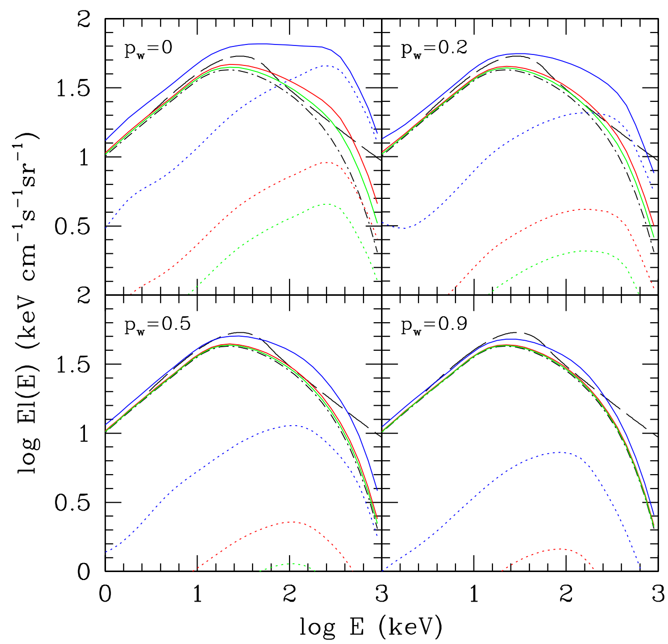

FIG. 2.— The contribution to XRB from bright and faint AGNs for the RIAFs with different wind strengths or without winds. The dashed lines are the observed XRB. The lines with different colors represent different values of $t^{\rm RIAF}/t^{\rm b}$=0.005(green), 0.01(red), and 0.05(blue), respectively. The dot-dashed line represents the contribution by bright type I/II AGNs (Compton-thin), which is taken from Ueda et al. (2003). The solid lines represent the XRB contributed by bright type I/II (Compton-thin) AGNs and the RIAFs in the faint AGNs, while the dotted lines are for the contributions of RIAFs in the faint AGNs only.

3. RESULTS

The three-dimensional MHD simulations suggest that the viscosity parameter α in the accretion flows is ~ 0.1 (Armitage 1998), or $\sim 0.05-0.2$ (Hawley & Balbus 2002). We assume a r-dependent accretion rate $\dot{m} = \dot{m}_{\rm out}(r/r_{\rm out})^{p_{\rm w}}$ for the RIAFs with winds. The parameters adopted in the calculations are: $\alpha = 0.2$, $\dot{m}_{\rm out} = 0.01$, the fraction of magnetic pressure $1-\beta = 0.5$ ($\beta = p_{\rm gas}/p_{\rm tot}$), and the fraction of dissipated energy directly heating electrons is: $\delta = 0.5$. The outer radius $r_{\rm out} = 100 R_{\rm Schw}$ is adopted in all our calculations, where $R_{\rm Schw} = 2GM_{\rm bh}/c^2$. We plot the X-ray spectra for RIAFs in Fig. 1.

There is no doubt that the contribution from a normal bright AGN is important in the VHXRB, as the *BeppoSAX* observations showed that the power-law X-ray spectra of bright AGNs extends to several hundred keV (e.g., Nicastro et al. 2000). Here we consider that the XRB consists not only of the emission from type I/II bright AGNs (Compton-thin) described by the HXLF, but also of the emission from RIAFs in those faint AGNs which are not included in the HXLF. In Fig. 2, we plot the results for the RIAFs with different wind parameters $p_{\rm w}$ for different ratios $t^{\rm RIAF}/t^{\rm b}$ ($\dot{m}^{\rm aver} = 0.1$ is adopted for bright AGNs).

4. DISCUSSION

We find that all spectra have an energy peak at around several hundred to 1000 keV (see Fig. 1). Compared with those obtained by Di Matteo et al. (1999), our spectra have higher energy peaks. The reason is that we adopt $\delta = 0.5$, larger than theirs, which leads to higher electron temperatures of the accretion flows. From Fig. 2, we find that $t^{\rm RIAF} \lesssim 0.05 t^{\rm b}$ is required from the comparisons of our theoretical calculations with the observed XRB, for any RIAFs either without winds or with strong winds. For the RIAFs without winds ($p_{\rm w} = 0$) or weak winds ($p_{\rm w} = 0.2$), we find that the hard X-ray emission alone from the RIAFs in faint AGNs have already surpassed the observed XRB, provided $t^{\rm RIAF} = 0.05 t^{\rm b}$. If the hard X-ray emissions from both the bright type I/II AGNs and RIAFs in faint AGNs are considered, we find more strict constraints on the RIAF timescale: $t^{\rm RIAF} \lesssim 0.01 t^{\rm b}$ required for most cases (it becomes $t^{\rm RIAF} \lesssim 0.005 t^{\rm b}$ for the RIAFs without winds). Here, we have neglected the contribution from the Compton-thick AGNs. If the contribution from a Compton-thick AGN is included, the present derived RIAF accretion timescales will become even lower.

Our present calculations are based on the assumption that all AGNs described by the Ueda's HXLF are bright, i.e., the standard bright accretion disks are responsible for their energy sources. Our RIAF spectral calculations show that $L_{\rm X}^{2-10{\rm keV}} = 1.48 \times 10^{41}$ergs s^{-1} for $p_{\rm w} = 0$, and 5.40×10^{40}ergs s^{-1} for $p_{\rm w} = 0.9$, respectively, if $M_{\rm bh} = 10^8 {\rm M}_\odot$ and $\dot{m}_{\rm out} = 0.01$. As the lower luminosity limit of the HXLF extends to $10^{41.5}$ergs

s^{-1}, it means that only the faint AGNs accreting at the critical rate with black hole masses $\gtrsim 2\times10^8 M_\odot$ may have appeared in this HXLF. The standard disks accreting at $\dot m > \dot m_{\rm crit}$ around a black hole with $\gtrsim 2\times10^8 M_\odot$ have $L_{\rm X}^{2-10\rm keV} \gtrsim 10^{42.5}$ ergs s^{-1}. This implies that some RIAF counterparts of the bright AGNs with $L_{\rm X}^{2-10\rm keV} \gtrsim 10^{42.5}$ ergs s^{-1} may be included in this HXLF. We can roughly estimate that the number ratio of these RIAF counterparts to bright AGNs with $L_{\rm X}^{2-10\rm keV} \gtrsim 10^{42.5}$ ergs s^{-1} is: $\lesssim t^{\rm RIAF}/t^{\rm b}$. Simply integrating the HXLF, we find that the ratio of the sources with $L_{\rm X}^{2-10\rm keV} = 10^{42.5-48}$ergs s^{-1} to all AGNs described by this HXLF is about 0.13, which implies that less than a fraction $\sim 0.13 t^{\rm RIAF}/t^{\rm b}$ of all sources with $L_{\rm X}^{2-10\rm keV} = 10^{41.5-48}$ergs s^{-1} may have RIAFs. Therefore, the contribution to the XRB from those RIAF sources with $L_{\rm X}^{2-10\rm keV} > 10^{41.5}$ergs s^{-1} may be over-calculated, but at a very low level of $\lesssim 0.13 t^{\rm RIAF}/t^{\rm b}$, which is negligible and will not affect our main conclusions.

We have assumed a constant lifetime $t^{\rm b}$ and $t^{\rm f}$ ($t^{\rm RIAF}$) for all bright and faint AGNs, which may not be true, as suggested by Hopkins et al. (2005). However, our results on the XRB only depends on the ratio $t^{\rm RIAF}/t^{\rm b}$, so our conclusions will not be altered, even if each individual sources have different lifetimes, provided they have a similar time-dependent form of $\dot m(t)$. The resulted XRB from Eq. (8) depends on the value of $\dot m^{\rm aver}$ as $\propto 1/\dot m^{\rm aver}$ (see Eq. 1). McLure & Dunlop (2004) estimated that the average accretion rate $\dot m^{\rm aver}$ varies from 0.1 at $z\sim0.2$ to 0.4 at $z\sim2$ from a large sample of SDSS quasars. If we adopt a larger $\dot m^{\rm aver} = 0.4$, the derived RIAF timescales $t^{\rm RIAF}$ will be four times of the present values. The derived timescales are proportional to the bolometric luminosity correction factor $f_{\rm cor}$, and the uncertainty of $f_{\rm cor}$ should not be very large, which will not affect our main conclusions. The emissions in hard X-ray bands from RIAFs are dominated by the bremsstrahlung emission and Comptonization of the bremsstrahlung photons (see Fig. 1), which are almost independent of β (magnetic field strength) adopted in the calculations.

Our results indicate that the accretion rate must drop to a very low rate from the critical accretion rate in a short timescale compared with the bright AGN lifetime. Recent hydrodynamical simulations on the evolution for the AGN formed after a merger indeed show a rapid decline of accretion rate from near Eddington rate to $\sim 10^{-5}$ within a short timescale compared with its bright phase (see Fig. 2 in Di Matteo et al. 2005), which is qualitatively consistent with our results. The black hole growth during the timescale $t^{\rm RIAF}$ can be neglected compared with that during the bright AGN phase, as $t_{\rm RIAF} \ll t^{\rm b}$. However, our present calculations have not considered how the accretion rate evolves with time in detail. The advection becomes important while the RIAFs are accreting at rates $\ll \dot m_{\rm crit}$, the black holes may swallow gases without radiating much X-rays. So, it cannot be ruled out the possibility that the faint AGNs stay at accretion rates far lower than the critical value for a very long time, say, comparable with the Hubble timescale. In principle, this can also be constrained by the cosmological XRB, which is beyond the scope of this *Letter*.

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